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Apparatus for RF Measurements

This inexpensive test set needs just an ac digital voltmeter along with the inherent precision of modern components to generate precise, very low level digitally modulated RF signals in the amateur HF bands.

We describe an RF test set that provides very accurate, very low power levels down to -150 dBm or less for testing the sensitivity of digital radios or for testing analog radios. While working to determine the sensitivity of receivers for digital modes, we needed an easy and convenient means to make low level RF measurements. An objective was to generate stable, low-noise signals and use them to accurately test digital modulation modes at very low signal levels, below -150 dBm. We wished to achieve this with relative simplicity, using methods that a home experimenter could apply to investigate receiver and transmitter performance, and the performance of digital modulation modes. Other key objectives were to produce a test set that was simple to calibrate, would be much lower in cost, and be smaller than a typical array of test equipment previously needed for this type of application.

The usual equipment list for these types of measurements includes several expensive pieces of RF test and measurement hardware. We launched into a project to design a digital radio test set. This is a brief discussion of the results.

Test Set Features

The test set is simple, low cost and can be used on a table top. It requires just an ac digital voltmeter for set-up and calibration, and features continuous level adjustment of the input audio signal. It provides for high performance, accurate, low level RF measurements.

The test set uses low cost microprocessor-type crystal controlled oscillators along with frequency division for stable, low noise signals. It enables comparisons of analog and digital modulation modes, and can be used with computer sound-card generated signals or with specialized digital modems commonly used with Amateur Radio communications, or with audio signal generators.

The test set can generate signals on the 20, 30, 40, 80 and 160 m bands in its standard basic configuration. It can be extended for use on other bands if desired, for a modest additional cost and parts count.

No electrical adjustments or measurements are necessary to change frequencies on the basic unit, which provides for standard receiver and transmitter measurements. The test set linearly translates modulated analog and digital RF signals to different frequencies in various amateur bands.

Features and uses are realized without the need for expensive test and measurement equipment. There is no need for RF step attenuators, stable well shielded laboratory grade RF generator, sensitive, accurate RF power meter, die cast aluminum or other shielded enclosures, costly RF connectors.

The Standard Test Set

Our original intent for this design was to make a test set that was low in cost, could be used on a table top, and not require large physical separation between transmitters and receivers. Especially important was the design goal of providing accurately known levels of RF power without requiring expensive test equipment, other than a good digital voltmeter.

The basic test set also generates accurately known RF power level unmodulated CW signals in the 10 and 15 m bands and signals within a few kilohertz of other bands. Provisions are made for adding modulated RF signals in other bands, with additional components and materials. However, an analysis of typical amateur band receiver architecture and operation will show that digital signal radio performance can be adequately measured using only one or two frequency bands, so additional frequencies are not really required. Receiver front ends are used at low levels of RF power, and handle signals in a very linear manner, so there is negligible distortion. Receiver noise figures may vary somewhat from band to band, but this is not a significant factor.

As usual, due to the external sources of noise at HF frequencies, the HF noise figure of the receiver is not a significant contributor to the signal to noise ratio of the desired signal to be processed. So, the performance of the digital signal modes, along with other modes, is determined by the RF receiver IF through to the audio systems, not the linear frequency-translating front ends, and primarily by the computer software performing the actual base-band signal processing and demodulation. Therefore, the modulation modes can be tested and compared using only the 160, 80, 40, or 20 m band where leakage signals can be more easily controlled using inexpensive cables and connections.

Local oscillator (LO) leakage into the receiver is mostly from the LO amplifier and its power supply circuits, causing RF energy on the coax shields and into the RF/IF printed circuit board, and from leakage across the mixer package — a surface mount package would be better but we had many of the metal can versions on hand. RG-400U double shielded coax with SMA connectors is used to connect the test board the to receiver. These leakage paths are manageable using 20 m signals due to the receiver's ability to filter out the LO that does get into it. The LO leakage is much reduced at 40 m and almost non-existent at 80 m when using inexpensive cable and RF connectors. However, fastening the 40 dB external attenuator directly to the receiver — through one SMA adaptor to the usual SO-239 connector — and using short lengths of RG-405 0.085 in/0.086 in semi-rigid cable — LO leakage is low enough to be of no concern at all frequencies.

Receiver Testing

For receiver, modem, and software testing, a modem — or a computer — provides the modulating audio signal to the test set. The ac voltmeter can be used to calibrate audio level, and hence ultimately the RF signal level. The test set is built on small PC boards using surface mount parts in order to reduce undesired RF radiation from the circuits and to provide predictable RF performance.

The RF output power from the test set is -73 dBm (nominal S9 level) for the fundamental frequency component on all bands, using only an audio range digital voltmeter at a level of 1 V. The 1 V signal passes through an accurate attenuation, and jumper-selected attenuation on the PC board, along with a means for variable attenuation, and into the mixer IF. This provides a continuously variable RF signal of known amplitude from -73 dBm down to -152 dBm. All attenuators are constructed using SMD 1% resistors — costing around 10 cents each — mounted on PC boards.

PSK31, RTTY, CW, and other modes have been successfully tested with these test sets, and basic minimum discernible signal (MDS) was measured on various receivers.[1] PSK31 signals have been decoded at known RF levels well below the receiver MDS (specified in the SSB bandwidth), or noise floor, at levels below -140 dBm. *Digipan* and *MMTTY* software were used to drive a SignaLink USB digital modem to modulate and demodulate signals.

Measuring Transmitters

The process could be reversed and a transmitter can be modulated with a modem, attenuated and used to insert a +10 dBm or less signal into the mixer at the RF port through the first 20 dB attenuator on the board. This makes a low gain, low sensitivity receiver to control unwanted RF signal radiation from the transmitter. This receiver is linear and has predictable performance. The IF output routes into the buffer amplifier to provide a modem with a signal to decode. This process tests the transmitter without a complex receiver in the path. Alternatively, once a receiver, modem, and software have been tested, transmitters can be operated into that combination and checked for signal quality.

Test Set Hardware and Techniques

A picture of the test set in use on the development bench is shown in Figure 1. The test set comprises two PC boards that are separated by the straight piece of coax cable seen in the photo. For lowest cost, we soldered cable connections, eliminating intermediate connectors.

One PC board, the LO generator portion of the test set, is seen in the upper center of Figure 1. The second board, the IF/RF portion of the test set, is seen in the lower center of Figure 1. The physical separation of the boards helps to avoid the need for shielded enclosures and expensive connectors. A different arrangement, better

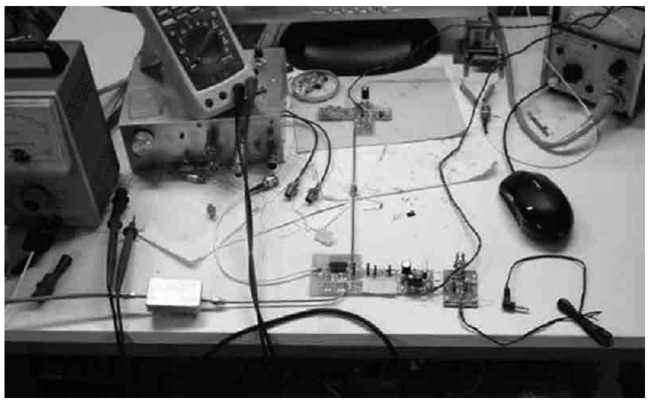

Figure 1 — The complete RF test set consists of the two PC boards separated by the straight piece of coax cable. For lowest cost, soldered-only cable connections can be used, eliminating any intermediate connectors. One board is at the top center, and connects by the vertical coax to the other board seen near the bottom center.

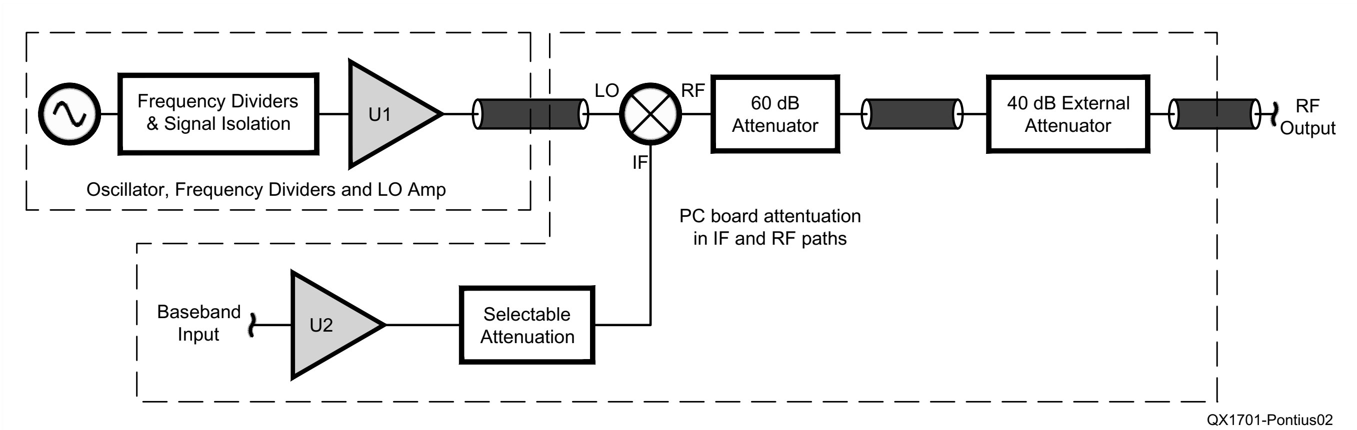

Figure 2 — Block diagram of the RF test set shows the oscillator, frequency divider, LO amplifier portion, and the mixer and attenuator portion.

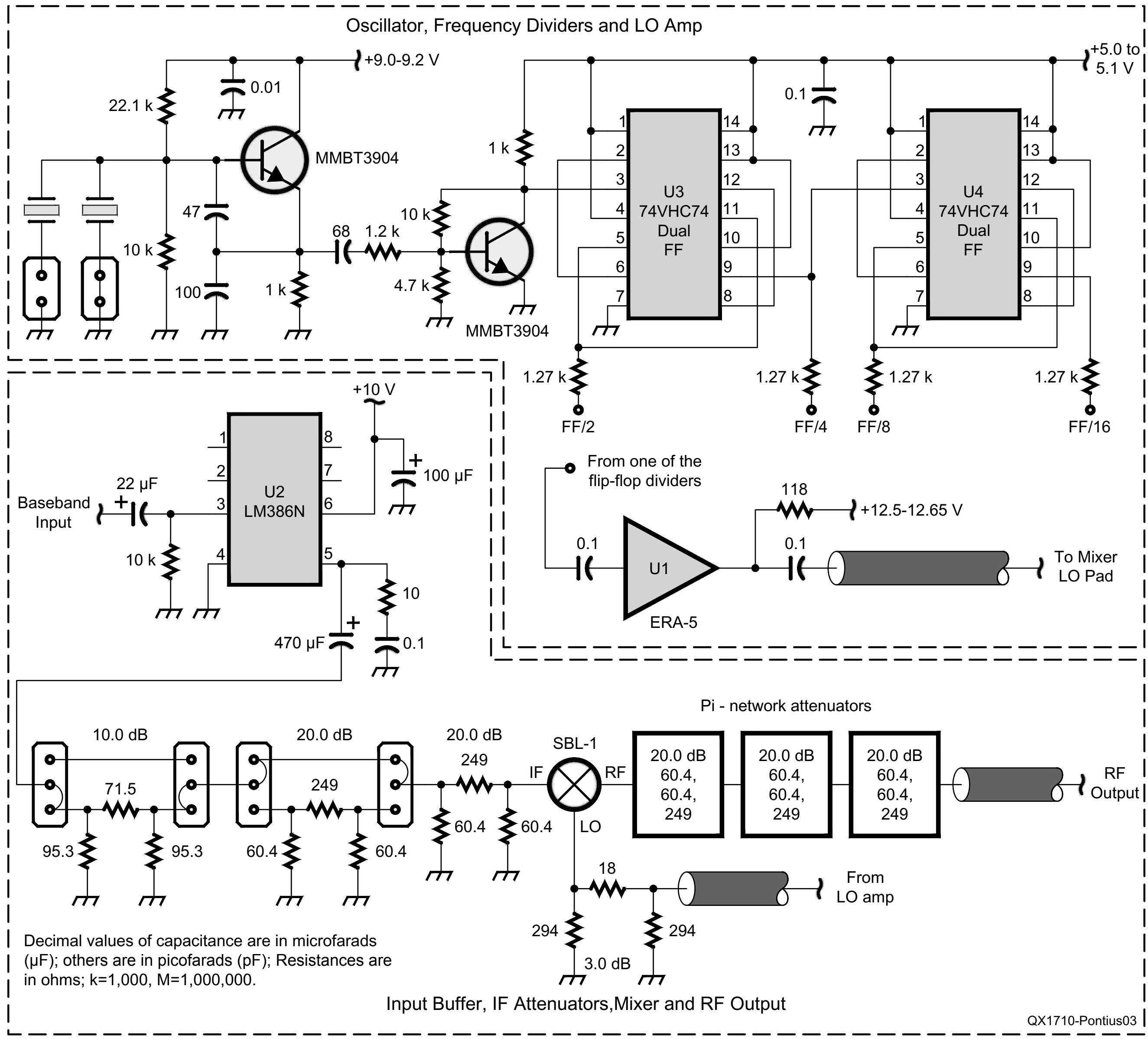

Figure 3 — Schematic diagram of the RF test set shows the components of the oscillator, frequency divider, LO amplifier PC board, and the components of the mixer and attenuator PC board.

than that shown in the picture, is a straight, in-line connection of the test set boards, as implied by the linear arrangement of the test set blocks shown in Figure 2.

When the external attenuator is used, it is screwed directly onto the receiver antenna connector through one adaptor. An RG405 coaxial cable attaches to the attenuator and is soldered to the RF output pad on the PC board. This in-line arrangement saves a cable and connectors, provides for low LO leakage into the receiver. Use a short piece of wire from the cable center conductor to a PC board pad. This makes it easy to connect and disconnect a cable, since the short wire is removed first, making it easy to then unsolder the cable jacket. The cable jacket can be soldered only on one side, rather than all around, making disconnections easier.

The external 40 dB attenuator is on the lower left side in the small shiny box — an Altoids box will also work — in the RF output line at the lower left in Figure 1. The circuit board on the lower far-right of the lower PC board, with the black audio cable attached, was used to connect to a computer for digital signal sources. This circuit is not required for normal use of the test set, but was utilized here for flexibility of sources that were used during development. A Signal Link USB modem with a low noise internal sound card was used along with a computer. The short white cable on the left side of the lower section was used during design and evaluation. Three of the units have been built and all accomplish the desired functions. To keep costs and complexity low, the test set was designed for use primarily with amateur transceivers having adjustable frequency, and available narrow crystal filters. However, there are techniques for working with crystal controlled, narrow tuning range, or fixed frequency low power PSK transceivers.

Block Diagram

A block diagram of the test set is shown in Figure 2, with schematic diagram shown in Figure 3. A crystal oscillator operating in the 28 MHz band is divided down by two dual flip-flops (FF), U3 and U4, to produce signals in the 20, 40, 80 or 160 m bands. Amplifier U1, a Minicircuits Labs (MCL) ERA-5 feedback amplifier, serves as the LO amplifier, and connects to one of the four frequency divider outputs corresponding FF/2, FF/4, FF/8 or FF/16 to the frequency desired. The mixer in Figure 2 is the MCL SBL-1.

In Figure 2 the signal at the LO mixer port is an RF tone. The signal in the IF mixer port is an audio tone or a baseband digital waveform. Its level is well know by measurement with a digital volt meter at the baseband input, measured at the U2 output. The signal out of the RF mixer port is a double sideband suppressed carrier RF signal — remember we are using a double-balanced mixer here. The output level is very nearly 6 dB below the level of the IF port signal.

Figure 3 shows the schematic diagram of the test set. The attenuators at the output of the mixer are surface mounted on the PC board, their implied topology is a Pi-network with 60.4 Ω shunt and 249 Ω series resistors. A 40 dB external attenuator, like the ones on the PC board, is also used. It is housed in a shielded Altoids box enclosure.

Figure 4 shows the IF/RF portion of the test set, also seen in the lower center of Figure 1. The LO signal comes in the top coax, and RF leaves by the lower coax. The IF path is in between. At the right is U2, a standard LM386N audio power amplifier driving the IF attenuators at 1000 mV. The IF attenuators are adjustable using the pins (headers) and shunts. The RF fundamental frequency output power is accurately set at -73 dBm (nominal S9 level) using only an audio range digital voltmeter.

Calibration Not Explicitly Needed

Levels are set by the inherent repeatable and reproducible characteristics of the components, as in the 1% resistor networks. The double-balanced diode mixers from Minicircuits have well known signal level characteristics. The transfer function of these devices, IF to RF and RF to IF, and LO to either RF or IF ports are well defined, controlled and specified, with much data available from MCL.

A signal at the IF port is mixed with an appropriate LO signal at the LO port to generate a known RF signal, by the well known transfer functions, both calculated and measured values. These transfer functions are consistent, and almost frequency independent, over the range of 3.5 to 29 MHz for a 1 to 500 MHz mixer device, like the MCL SBL-1. The SBL-1 uses a 7 dBm LO.

You can measure these responses with a wide-band thermal power meter like the HP-478A/432A power meters, a spectrum analyzer, a DSO, or a calibrated receiver. We used them all to verify performance. The output at the RF port from a 0.1 V (100 mV) ac source, at say 1 kHz, at the IF port, will result in predicable stable signals at the RF port of -13 dBm (within a few tenths of a decibel) for each sideband of the fundamental signal.

For a “calibrated result” all we need to do is measure the voltage available to the IF port using a low frequency ac voltmeter in order to know the RF output within a few tenths of a decibel. The fundamental value of each sideband of the ac IF signal at the RF output will be very close to -13 dBm. Then the accurate 60 dB attenuator on the PC board will yield the -73 dBm signal.

Three 20 dB precision attenuators on the PC board provide 60 dB of RF attenuation. A 40 dB external RF attenuator, like the one seen in Figure 1, plus a jumper selectable 0, 10, 20, or 30 dB of IF fixed attenuation is used, along with variable IF attenuation by adjusting the audio range signal level at the LM386N buffer amplifier output (10 to 12 dB range) using the ac digital voltmeter. This provides a continuously variable RF signal of known amplitude from -73 dBm to -152 dBm. The SMD attenuators on the PCB and the external 40 dB attenuators correlated well when compared to two HP 355D and two Kay Elemetrics 439A attenuators, and Pasternack attenuators.

The 1 V ac IF input signal results in a 0.1 V signal available to the mixer IF port. This creates an upper and a lower sideband at the mixer RF port. The receiver selects either sideband and rejects the other. When a 1 V dc signal is inserted at the IF attenuator chain, by opening the connection from the IF buffer amplifier, the sidebands merge into a single signal at the frequency of the LO. The power measured at the RF port of the mixer will be exactly 3 dB higher than the individual sidebands were when an ac IF signal was used.

Figure 5 shows the LO generator portion PC of the test set, also seen in the upper center of Figure 1. The circuit includes, left to right, a crystal oscillator, TTL type conditioner/FF driver, dual flip-flops U3 and U4, and (bottom) LO amplifier. The LO signal exits the bottom center at a level of about +10 dBm. This level is set by the consistent, frequency independent, and known level at the FF outputs, and by the consistent, frequency independent, and known gain of the feedback RF amplifier (the SMD ERA-5). The LO frequency is changed, if desired, by attaching the appropriate FF output wire to the LO amp input. No adjustments are required.

The crystal oscillator typically runs

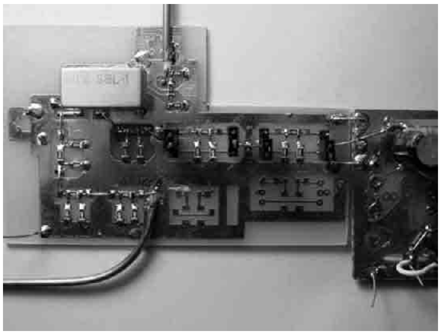

Figure 4 — The IF/RF PC board portion includes the mixer and attenuators.

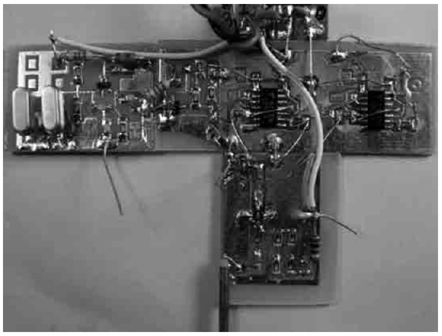

Figure 5 — The local oscillator, LO amplifier, frequency divider / flip-flop PC board.

at 28.220 MHz, or with other 70 cent microprocessor crystals in the 7 to 28.5 MHz range. The four (two per package) FFs in the center divide the 28.220 MHz by 2, 4, 8 or 16 to obtain 20, 40, 80 or 160 meter signals from the 28.220 MHz (or some other frequency in that range). The LO amplifier at lower center is simply jumper-tapped onto the desired FF output. There are no tuned circuits and no adjustments required for changing bands of operation. The conditioner circuit limits the oscillator signal to a 5 V square wave for the FFs. RF levels are determined by known levels at the FFs and the constant known gain of the LO amplifier to yield an LO drive within about -0.5 to +1 dB of the desired +7 dBm without needing to make any RF measurements. There is a 3 dB attenuator at the mixer LO input on the IF/RF PC board.

The voltage from the adjustable IF buffer amplifier, and the precision attenuators determine the RF output. Signal leakage is adequately low and LO leakage and feed-through are controlled, to afford accurate measurements. The FFs divide the frequency for stability and lower noise, but they also provide a degree of signal isolation by separating the oscillator signal from the LO value being used. The small size of the SOIC packages keeps unwanted radiation down. These features help to avoid the need for expensive shielded enclosures and expensive RF connectors.

Conclusions

By exercising care, all receiver measurements can be accomplished with adequate accuracy, and modem performance can be evaluated. The process can be reversed and a transmitter can be modulated with a modem, attenuated and used to insert a +10 dBm or less signal into the mixer at the RF port through the first 20 dB attenuator on the board. This makes a low gain, low sensitivity receiver to control unwanted RF signal radiation from the transmitter. This receiver is very linear and has predictable performance. The IF output is routed into the buffer amplifier to provide a signal for the modem to decode. This process tests the transmitter without a complex receiver in the path. Alternatively, once a receiver, modem, and software have been tested, transmitters can be operated within that combination and checked for signal quality.

Our circuit boards were cut apart from one 5 in long by 3.3 in wide PC board that was manufactured by Far Circuits.

Modulators could be tested using RF links by linking two of these test sets together. The set on the transmitter side can use fewer on-board attenuators. Modems can also be tested by directly connecting them to each other without any RF. Additionally, controlled noise levels can be inserted into the test procedures using op amps and a noise generator.

Bruce Pontius, NØADL, holds a BSEE degree and has been involved in the development of RF semiconductors, radio equipment and systems for many years. He participated in the development of early cellular radio equipment, digital trunking radios and narrowband data radio equipment. Bruce served as Engineering Vice President at E.F. Johnson Company for 15 years and worked with other companies in similar roles. He served as President of TRM Associates, working in wireless communications and RFID, until he retired. Bruce first got involved with Amateur Radio at age 11, building radios and test equipment with his father. He holds an Extra Class license and enjoys operating with simple equipment, portable operation, and doing RF tests and measurements.

Kazimierz (Kai) Siwiak, KE4PT, earned his PhD specializing in antennas, propagation and digital communications. He is a registered Professional Engineer and Life Senior Member of IEEE. Dr. Siwiak holds 41 US patents, has authored many professional papers and several textbooks. His writings appear in QST, QEX, and other ARRL publications. Kai holds an Amateur Extra class license, is a life member of AMSAT, and member of ARRL where he serves on the RF Safety Committee, is a Technical Advisor, QEX Editor, and QST Contributing Editor. He is an avid DXer and QRP operator, and was a team member with SAREX (Space Amateur Radio Experiment). His interests include flying (instrument and multiengine commercial pilot), hiking, and camping.

Notes

[1]K. Siwiak, KE4PT, and B. Pontius, NØADL, "How Much 'Punch' Can You Get from Different Modes?", *QST*, Dec 2013, pp 30 – 32.